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Integration of hydrogen energy technologies in stand-alone power systems analysis of the current potential for applications

E.I. Zoulias[a,*], R. Glockner[b], N. Lymberopoulos[a], T. Tsoutsos[a,e], I. Vosseler[c], O. Gavalda[c], H.J. Mydske[b], P. Taylor[d]

[a]*Centre for Renewable Energy Sources (CRES), 19th km Marathon Ave, GR 19009 Pikermi, Greece*
[b]*Institute for Energy Technology (IFE), Instituttveien 182027, Kjeller, Norway*
[c]*Trama Tecnoambiental (TTA), Ripolles Barcelona 4608026, Spain*
[d]*Econnect, Energy House, 19 Haugh Lane Industrial Estate, Hexham, Northumberland NE46 3PU, UK*
[e]*Department of Environmental Engineering, Technical University of Crete, GR 73100 Chania*

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Abstract

The European study entitled: “Market Potential Analysis for Introduction of Hydrogen Energy Technology in Stand-Alone Power Systems (H-SAPS)” aimed to establish a broad understanding of the market potential for H-SAPS and provide a basis for promoting in wide scale new technological applications.

The scope of the study was limited to small and medium installations, up to a few hundred kW power rating and based on RE as the primary energy source. The potential for hydrogen technology in SAPS was investigated through an assessment of the technical potential for hydrogen, the market analysis and the evaluation of external factors.

The results are mostly directed towards action by governments and the research community but also industry involvement is identified. The results include targeted market research, establishment of individual cost targets, regulatory changes to facilitate alternative grid solutions, information and capacity building, focused technology research and bridging the technology gaps.

Keywords: Stand-alone power systems; Hydrogen; Fuel cells; Market potential analysis; Renewable energy sources

* Corresponding author. Tel.: +30 2106603327; fax: +30 2106603301.
E-mail address: mzoulias@cres.gr (E.I. Zoulias).

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Contents

1. Introduction

A study was undertaken to determine the potential for the introduction of environmentally benign hydrogen technologies in what is believed to be a near term opportunity, namely stand-alone power systems (SAPS) [1].

SAPS are defined as non-grid connected electrical power systems, an increasing number of which includes local renewable energy (RE) technologies, i.e. solar or wind power, most often in combination with diesel generators and/or batteries for backup power. However, the majority of larger SAPS are still based on fossil fuel power generation.

A study was undertaken aiming to:

- establish a broad understanding of the technical and economical market potential for H-SAPS based on local renewable energy sources (RES) and to form a basis for industry and governments to promote new technological applications.
- identify and quantify the technological and practical issues relevant for the H-SAPS market. The work also drew the attention to related industry towards solving problems related to component integration and the needs of the user market.
- identify the legal, regulatory and administrative hurdles for H-SAPS market development and recommend ways in which the authorities might resolve these issues.
- propose a demonstration project plan for H-SAPS installations.

The scope of the study was limited to small and medium sized SAPS (power rating up to 300 kW) and based on RE as the primary energy source. Power supply for both domestic and commercial applications was included in the study. However, uninterruptible power supply systems or other types of back-up power systems installed in areas, where grid connection is available, were not considered. RE technologies, which have readily available energy storage capacity, were not included. Furthermore, tidal and wave energy were not included in the study because the technology for harnessing these resources is not–technically and economically—mature at the time. Particular attention was paid to the application of fuel cells (FCs) for re-electrification of hydrogen. However, the technological potential for internal combustion engines (ICE) in H-SAPS was also addressed [2,3].

2. The SWOT analysis

2.1. The SWOT analysis tool

The potential for H-SAPS arises from inherent technical challenges in SAPS and technological limitations on conventional SAPS technology. Furthermore, there are additional numerous parameters in the energy market, in the policy framework, but also in society that will influence the potential realisation of H-SAPS.

A SWOT analysis was done initially in order to map the most obvious success factors. The initial structuring of these success factors was undertaken in accordance with the SWOT methodology (Strengths, Weaknesses, Opportunities and Threats). *Strengths* and *Weaknesses* refer to the hydrogen in SAPS (H-SAPS) and constitute so-called internal factors, which may be influenced. *Opportunities* and *Threats* refer to the external environment affecting market development of the H-SAPS.

The S, W, O and Ts of H-SAPS were identified, then new elements were added and the SWOT analysis was quality assured by means of workshops and questionnaires that were sent to interested parties (e.g. RE technology providers, hydrogen technology providers, system operators and users) [4].

After the identification of the S, W, O and Ts in the SWOT exercise, success factors were assigned to each S, W, O and T. These success factors were divided into three categories:

- Market
- Technical
- Environmental effects and RE utilisation

In order to evaluate the different success factors, different tools and approaches were applied. These are described in more details in Chapter 3. In the final stage of the study, a number of policy recommendations emerged from the results and conclusions. Finally, a demonstration plan, with two suggested hydrogen demonstration sites, was put forward.

2.2. First inputs and orientation

The SWOT analysis played a key role in the methodology. It was initially carried out among the authors as a first step exercise drawing from their own experiences, knowledge and contacts. This provided preliminary critical success factors and focus for the data collection phase

The information flow from these activities was fed into the SWOT analysis. The objectives were to:

- Obtain a reality check on the critical success factors
- Gain additional feedback
- Update and add to the critical success factors

Fig. 1 shows how the various activities were interlinked.

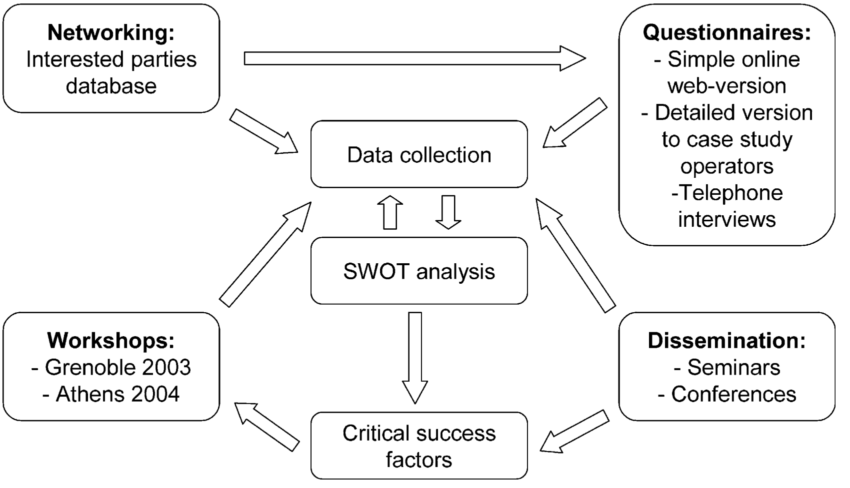

Fig. 1. A schematic representation of how the different activities were interlinked.

The complete SWOT analysis including critical *Success Factors* for *Technology*, *Market* and *Environment* is shown in Tables 1–3, respectively.

The sorted tables helped to focus on the presumed main success factors that affect the H-SAPS potential all the way through the data collection, the analyses and, finally, recommendations. Furthermore, it served as a structure and methodology where new success factors could be introduced as they were identified [3].

2.3. Critical success factors

The critical success factors, namely improving the Strengths and Opportunities and eliminating the Weaknesses and Threats, were categorized according to their relevance to three main areas:

- Technology
- Market
- Environment

There was a degree of overlap between the S, W, O and Ts from the SWOT analysis for the three different categories: *Technology*, *Market* and *Environment*, as can be seen in Table 4.

3. Data collection and analysis

The potential for hydrogen technology in SAPS was investigated through an assessment of:

- the technical potential for hydrogen in SAPS (evaluation of hydrogen technology components, case modelling of hydrogen in existing conventional SAPS, assessment of existing H-SAPS demonstration plants);

Table 1
Strengths, weaknesses, opportunities and threats and critical success factors for the technology

	Strengths	Weaknesses	Opportunities	Threats	Critical success factors
Technology	1. Already existing experience in handling of compressed gases 2. Noise level of the main competing systems (e.g. DEGS) 3. Potential for high density energy storage 4. Seasonal energy storage without energy loss over time 5. Able to handle power fluctuations and therefore ideal for integration with intermittent RES 6. Guaranteed power from a RES system 7. Potential for low and predictable O&M costs 8. Self-sufficient energy supply	1. Technology immaturity of FCs and PEM electrolysers 2. Low availability and high cost of small electrolysers 3. Procurement cost 4. Lack of component and system life-time experience 5. Low component efficiency	1. Emergence of large scale markets for hydrogen	1. Limited practical experience due to few true H-SAPS installed 2. Competing technologies prove to be perfectly adequate	1. Self-sufficient energy supply 2. Competing technologies prove to be perfectly adequate 3. Emergence of large scale markets for hydrogen 4. Limited practical experience due to few true installed HSAPS

Table 2
Strengths, weaknesses, opportunities and threats and critical success factors for the market

	Strengths	Weaknesses	Opportunities	Threats	Critical success factors
Market	1. No need for fuel transport infrastructure	1. Missing codes and standards (safety issues, technical specifications, etc.)	1. Already existing SAPS in which hydrogen technologies can be incorporated	1. Potential end users have no experience	1. New job opportunities
	2. Already existing experience in handling of compressed gases	2. Low availability and high cost of small electrolysers	2. Current EU and national financing schemes	2. No public available market study for SAPS in EU	2. Limited practical experience due to few true H-SAPS installed
	3. Self-sufficient energy supply	3. Lack of after-sales support	3. New job opportunities	3. Inadequate commercialisation plan	3. Inadequate legislative framework (standards, regulations, permissions of installation)
		4. Weak supply network (consultants, engineers, entrepreneurs, etc)	4. Diversification of companies involved in the energy sector	4. Limited practical experience due to few true H-SAPS installed	4. Lack of awareness of capabilities and potential benefits of hydrogen
		5. Few dedicated complete system deliverers	5. Energy costs in SAPS relatively high	5. Hydrogen as a storage medium for energy in SAPS is not known and accepted	5. No public available market study for SAPS in EU
		6. Lack of awareness of capabilities and potential benefits of hydrogen	6. No one industry standard technological solution for SAPS	6. Inadequate legislative framework (standards, regulations, permissions of installation)	6. No one industry standard technological solution for SAPS
				7. Low interest and priority from utilities and major suppliers of SAPS components/systems	
				8. Competing technologies prove to be perfectly adequate	
				9. SAPS owners/end-users refuse to accept the new technology	
				10. Not enough players enter the market	
				11. Negative common perception of the large scale impact of hydrogen on climate change	

Table 3
Strengths, weaknesses, opportunities and threats and critical success factors for the environment (environmental and RE utilisation)

	Strengths	Weaknesses	Opportunities	Threats	Critical success factors
Environment	1. Noise level of the main competing systems (e.g. DEGS) 2. Potential for high density energy storage 3. Able to handle power fluctuations and therefore ideal for integration with intermittent RES 4. Reduced environmental impact compared to conventional energy sources 5. Guaranteed power from a RES system	1. Lack of recycling and re-use schemes for hydrogen technology	1. Reduction of environmental impact 2. Replace/reduce batteries, diesels	1. Negative common perception of the large scale impact of hydrogen on climate change	1. Negative common perception of the large scale impact of hydrogen on climate change 2. Guaranteed power from a RES system 3. Lack of recycling and re-use schemes for hydrogen technology

Table 4
The critical success factors identified through the SWOT analysis

Category	Critical success factor
Technology	1. Self-sufficient energy supply
	2. Competing technologies prove to be perfectly adequate
	3. Emergence of large scale markets for hydrogen
	4. Limited practical experience due to few true H-SAPS installed
Market	1. New job opportunities
	2. Limited practical experience due to few true H-SAPS installed
	3. Inadequate legislative framework (standards, regulations, permissions of installation)
	4. Lack of awareness of capabilities and potential benefits of hydrogen
	5. No public available market study for SAPS in EU
	6. No one industry standard technological solution for SAPS
Environment	1. Negative common perception of the large scale impact of hydrogen on climate change
	2. Guaranteed power from a RES system
	3. Lack of recycling and re-use schemes for hydrogen technology

- the market analysis (demand side, supply side);
- the evaluation of external factors.

The main results of these activities are explained in the following sub-sections.

3.1. Technology

The technical potential for hydrogen technology in SAPS was investigated on the basis of three main areas of activity:

1. Review of literature on existing H-SAPS demonstration plants
2. Evaluation of hydrogen technology components based on literature and contact with suppliers
3. Modelling of existing SAPS in their current state and with hydrogen (H-SAPS)

Critical parameters for the introduction of hydrogen technology components in SAPS were defined in order to link the evaluation to the specifics of H-SAPS. The critical parameters are: safety, market readiness, availability (start up times, O&M service), reliability, costs (Investment and O&M), lifetime, flexibility as power source or sink, physical size and energy efficiency.

Based on the three methods described above, these critical parameters were evaluated on a semi-quantitative basis. This means that, where quantitative measures for the parameters were found, such as for costs, availability, flexibility as power source or sink, physical size and energy efficiency, these were given. This assessment was carried out to assist stakeholders to evaluate the choice of technology for certain stationary H-SAPS applications and technology developers to identify barriers for the use of hydrogen technology in H-SAPS.

3.1.1. Technology evaluation

3.1.1.1. Hydrogen technology components. The hydrogen components were classified by production, storage and utilisation. For hydrogen production from intermittent RES, splitting of water through the process of electrolysis is a commercially available option. The types of electrolysers considered were the so-called polymer electrolyte membrane (PEM) and alkaline.

In general, there are two commercially available storage options for hydrogen; (1) compressed gas and (2) liquefied gas. These storage techniques are well established and mature. In addition, an interesting storage option comprising storage of hydrogen in metal hydrides was investigated. Metal hydride storage tanks are available on a pre-commercial basis—with several companies on the verge of commercialisation. Given the size definitions in the H-SAPS study, storage of hydrogen as a liquid was considered to be too complex, costly and energy inefficient.

Although FCs represent a technique for re-electrification of hydrogen with high energy efficiencies, they are currently available only on a pre-commercial basis. As a possible bridging solution, ICE running on hydrogen was also investigated. Hydrogen ICEs are technologically more mature and have a significantly lower cost. There are FCs of different types depending on, for instance, their operational temperature. In an early selection process it was decided to focus on low-temperature FCs namely PEM and alkaline type FCs.

In addition to setting the technology status and potential in SAPS, the potential technological improvements for each of the components were described to give a foresight regarding their future suitability for SAPS.

Experience of the integration of hydrogen technology in SAPS has also been gained worldwide through demonstration projects. The most relevant of these demonstration projects were taken into consideration in the study.

From the different approaches to determining the potential for hydrogen technology in SAPS a number of conclusions were reached:

3.1.1.2. Hydrogen production. Alkaline electrolysers constitute mature technologies for medium- to large-scale hydrogen production based on predictable and stable power input. Over recent years, however, several companies in Europe have appreciated the fact that distributed generation of hydrogen from RES will be one of the first applications of hydrogen technology—the reasons being comparatively high prices for fossil fuel and transport for these systems. Hence, new developments of smaller units, which may be operated on fluctuating RES, have been taking place. The development of PEM electrolysers is interesting as they provide compact systems having a potential for high-pressure output and flexibility to accommodate power fluctuations. These solutions are, however, far too expensive and have low lifetime warranties and little lifetime experience to date. PEM electrolysers are available only on a prototype and pre-commercial basis and are limited in size up to 10–20 Nm^3/h. Hence, even though small alkaline electrolysers are also relatively costly due to a small market, they are the preferred solution for H-SAPS today. Fig. 2 shows the collected cost information on electrolysers with production hydrogen capacity 1–120 Nm^3/h. The dotted line only provides a guide to the eye. As a follow-up of

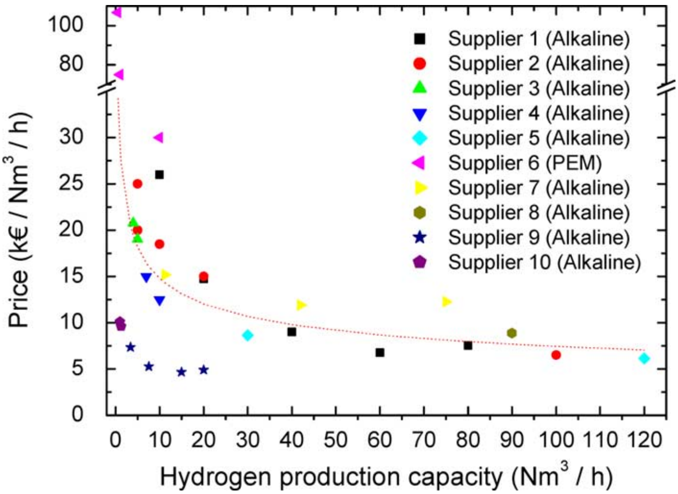

Fig. 2. Electrolyser component costs obtained from 10 major suppliers in Europe.

the current study, Solid Oxide electrolysers could be considered in the future due to their suitability for solar thermal and solar electric applications.

3.1.1.3. Hydrogen storage. Metal hydrides are sold on a pre-commercial basis and may, as such, be considered an alternative to compressed gas storage options. The cost assessment, which was undertaken in this study, however, shows that metal hydrides may compete in price only at small storage capacities (some tens of Nm^3), even in the long-term. This will be the case only if no breakthrough in metal hydrides, made from cheaper materials and through less energy demanding materials processing, surface. There are also clear limitations to the use of metal hydride storage solutions in H-SAPS. First of all, the limitation in flow-rate discussed in Section 3.1.1.2 would put limitations on the use of metal hydrides in H-SAPS applications where fast charge and discharge of hydrogen compared to the size of the system is experienced. This would apply typically to emergency power systems, hydrogen filling stations, special technical installations, etc. A more severe limitation is perhaps the need for heat integration in order to charge and discharge metal hydrides especially in outdoor applications in cold areas, where the discharge pressure will drop and discharge will demand heat integration. However, the heat management of metal hydrides may also prove an advantage for some energy systems. This is due to the fact that hydrogen compression will be available without costly (investment and O&M costs) and noisy compressors. In addition, safety consideration may render metal hydrides the preferred solution. This might apply to distributed storage systems, for instance, in households where safety is particularly important.

The economically favourable storage solution was found to be conventional steel tanks for pressurised hydrogen gas. Fig. 3 shows the collected cost data for low- and high-pressure steel tank solutions. The dotted line shows the fit used in the techno-economic assessments used for medium scale storage tanks.

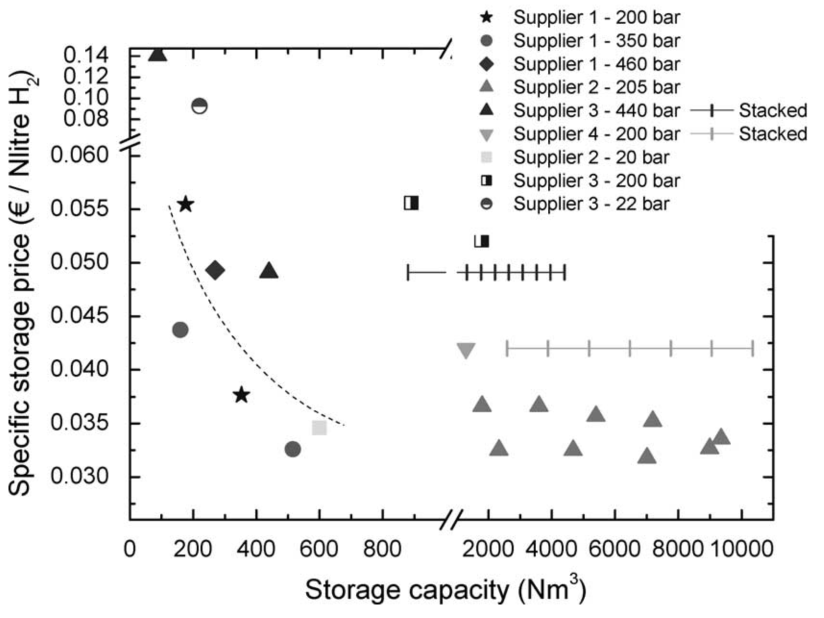

Fig. 3. Price/capacity relations for commercially available compressed storage options for hydrogen in the medium- to large-scale range.

3.1.1.4. Re-electrification technologies. FCs for the production of heat and electricity are available on a pre-commercial basis, but the lifetime warranty is too short and the prices far too high in order for these solutions to be competitive at present (2004). Indicatively the prices of PEM FCs range from 6000 to 10,000 €/kW. ICEs represent a transition technology for H-SAPS in the shorter term. ICEs have lower energy efficiencies than FCs, which will limit the potential in energy systems where long-term storage of energy as hydrogen is needed. The costs of ICEs are also still high; 2000–3000 €/kW, but the potential for cost reduction, given a market, is significant. There is no technical reason why ICEs on hydrogen should not reach the costs of natural gas engines, which are presently around 300–400 €/kW. ICEs are applied in a number of demonstration plants and may be a bridging technology until FCs will be available at acceptable costs and lifetime expectancy. Alkaline FCs represent a promising and potentially far less expensive option compared to PEMFC. The AFC companies have reported a cost target of less than 200 €/kW for the FC stack costs in 3–5 years, while SOFC companies have projected costs at $150–200/kW. But it still remains unclear whether the expectations in price, lifetime and operability for alkaline FCs will be met in the near future.

3.1.1.5. System level experience. Information from several H-SAPS demonstration projects was assessed in order to try to identify component and system level barriers for introduction of hydrogen technology in SAPS. Table 5 shows a list of demonstration projects where stand-alone operation has been one of the main objectives. This list is not exhaustive, but is

Table 5
Existing Stand-alone power systems (SAPS) based on renewable energy as an energy source and hydrogen as an energy carrier

Project	Country	Components[a]	Ref.	Peak power generation (W)	
				PV	Wind
Small size (<10 kWp)					
NEMO	Finland	PV-BAT-ELY-Store(LP)-FC	[5]	1300	–
Self-sufficient solar house in Freiburg	Germany	PV-BAT-ELY-Store(LP)-FC	[6]	4200	–
SAPHYS	Italy	PV-BAT-ELY-Store(LP)-FC	[7]	5600	–
INTA	Spain	PV-ELY-Store(LP,HP,MH)-FC	[8]	8500	–
IFE-H-SAPS	Norway	PV-ELY-Store(MH)-FC	[9]	2000	–
Medium size (10–100 kWp)					
Trois Rivieres	Canada	Wind-PV-ELY-Store(LP)-Bat-FC	[10,11]	1000	10,000
Fachhochschule Stralsund	Germany	Wind-ELY-Store(LP)-FC	[12]	–	100,000
CREST-HaRI-project[b]	UK	Wind-PV-ELY-Store(LP,MH)-FC	[13]	13,000	50,000
Large size (>100 kWp)					
The Utsira project[b]	Norway	Wind-Stor(LP)-FC,ICE	[14]	–	600,000

[a] PV, photovoltaics; ELY, electrolyser; BAT, battery; store, hydrogen storage unit; LP, low pressure compressed gas (<10 MPa); HP, high pressure compressed gas (>10 MPa); MH, metal hydride storage unit, FC, FC; ICE, internal combustion engine running on hydrogen.
[b] In installation phase (2004).

believed to represent some of the most interesting demonstrations projects linking RE and hydrogen in the size range of the H-SAPS study.

In the late 1980s and early to mid 1990s focus was on production of hydrogen from photovoltaics (PV). There has been a renewed focus on the PV to hydrogen connection over recent years, but wind has also entered the scene as an important RES for H-SAPS. Another general observation is that stand-alone operation or partly stand-alone operation has become more of an issue over the last 5 years.

Most of the projects in Table 5 applied alkaline electrolysers for generation of hydrogen from RE. In general, it was stated that the alkaline electrolyser technology was mature enough for solar and wind applications. However, the need for more long-term testing of deterioration of hydrogen yield when applying intermittent energy was emphasised. The most frequent reason for plant shutdowns amongst the listed projects was failure of electrolyser auxiliary components (water demineralisation unit, compressed air treatment unit and inert gas flushing).

Another general concern was the complexity and parasitic energy losses of the hydrogen energy systems due to the need for gas control. Hence, controllers, compressors, converters and gas cleaning equipment increased the complexity compared to conventional SAPS and also reduced the overall energy efficiency. For the small H-SAPS systems (<10 kW), it was stated that the parasitic losses of the auxiliary units was a special concern as it reduced the overall energy efficiency of the hydrogen energy system. This points to the need to make available dedicated control units for H-SAPS with smaller control ranges and hence with

lower energy consumption. It also emphasises that, in a future market for H-SAPS, dedicated H-SAPS system deliverers/installers with generic turnkey solutions are essential.

3.1.2. Techno-economic modelling

Techno-economic modelling of five existing SAPS systems utilising the HYDROGEMS library was conducted. These five cases were chosen on the basis of diversity in climate conditions, RE technology, power demand and load characteristics. The study partners have been involved at one or more stages of the installation of SAPS and the five SAPS systems selected from their portfolio provided the required diversity. They represented four climatically different parts of Europe, including technologies as PV, wind and small hydro, ranging from 8 to 70 kW and including both seasonal and all year load characteristic [15]. The five cases were:

• Kythnos (Greece)	PV–diesel–battery
• Fair Isle (UK)	Wind–diesel
• Rum (UK)	Micro-hydro–diesel
• Rauhelleren (Norway)	Diesel only
• La Rambla del Agua (Spain)	PV–battery

The economic assumptions were an important input to the modelling activity. These were identified from a search through available literature and direct contact with hydrogen and renewable energy technology manufacturers. The linear cost models for the given capacity limitation of the H-SAPS study are given in Table 6. Non-linear cost models for other components of SAPS are given in Table 7.

In order to estimate the future competitiveness of H-SAPS, an extrapolation of the costs of hydrogen technology was undertaken. The present and future cost assumptions are summarised in Table 8.

The modelling produced realistic capacities for the realisation of H-SAPS (with the given power limitations of the H-SAPS study) even at the present time (2004). The economy of hydrogen solutions is, however, strongly dependent upon the site characteristics. Fig. 4 shows the cost of energy (COE) of all five cases at present (2003–2005) and in the long-term based on the assumption described in Tables 6 and 7.

Table 6
Linear cost model assumptions used in the techno-economic modelling

Component description	Cost model validity range			Cost fit parameters linear model $Y=A+B\times X$		Lifetime (years)	O&M (% of invest-ment)
	From	To	Unit	A	B		
WECS	15	200	kW	0	1400	30	1.5
Micro-hydro	15	35	kW	0	2400	20	1.5
PV	0	inf	kW	0	6750	30	0.0
Electrolyser	2	120	Nm^3/h	0	8150	20	2.0
H_2-storage unit	5	10,000	Nm^3	0	38	20	0.5
FC	5	50	kW	0	3000	10	2.5
Battery	0	1000	kWh	0	100	7	1.0

Table 7
Non-linear cost model assumptions used in the techno-economic modelling

Component description	Cost model validity range			Cost fit parameters capacity factor model $(I_0/I)=(C_0/C)^n$			Lifetime (years)	O&M (% of investment)
	From	To	Unit	I_o	C_o	N		
DEGS	5	50	kW	394	24	0.66	6	2.0
Diesel tanks	1	60	m^3	204	25	0.3	30	0.0

The large variations in costs for the conventional systems are due to the different RE technologies (electricity from PV being 2–3 times more expensive than wind), varying diesel costs (varying transportation costs) and other site characteristics such as RE and load match. The system modelling showed that the cost of H-SAPS is high and that the main problem is to limit the storage demand. A direct consequence of this would be to ensure that any plant should be as much as possible configured with regards to RES and match of RES and user load.

Another important issue is the division of electrical and thermal load in order to raise the total energy efficiency of the hydrogen energy system. In addition, it is important to recognise the need for prioritising loads by introducing load control, which is already operating successfully in a number of conventional SAPS. This is a powerful tool in reducing COE for the system. Control systems with incentives for the use of energy in times of surplus RE are another means of reducing the investment costs for storage of energy as hydrogen in SAPS.

Electrolyser and storage units contribute significantly to the overall system costs. Electrolyser cost reduction is then equally important compared to the cost reductions for FCs for this early market segment. At present, the hydrogen technology industry can

Table 8
Assumed lifetime and operations and maintenance cost, and estimated specific costs for the hydrogen energy system components today and in 2020

Hydrogen technology component	Type	2003–5			Long-term (2020)		
		Lifetime (years)	O&M (% of inv. costs)	Cost	Lifetime (years)	O&M (% of inv. costs)	Cost
Electrolyser	Alkaline (3 MPa outlet pressure)	20	2.0	8150 €/ Nm^3/h	20	1.0	4075 €/ Nm^3/h[a]
FC	PEM-type	10	2.5	3000 €/ kW	20	1.0	300 €/ kW[b]
H_2-storage unit	Compres-sed gas (3 Mpa)	20	0.5	38 €/Nm^3	20	0.5	25 €/ Nm^3[c]

[a] A 50% reduction in cost is assumed.
[b] EU-target cost for stationary applications in the long-term (here defined as 2020).
[c] 30–40% reduction in cost assumed by the steel tank producer Holger Andreasen GmbH, private communication.

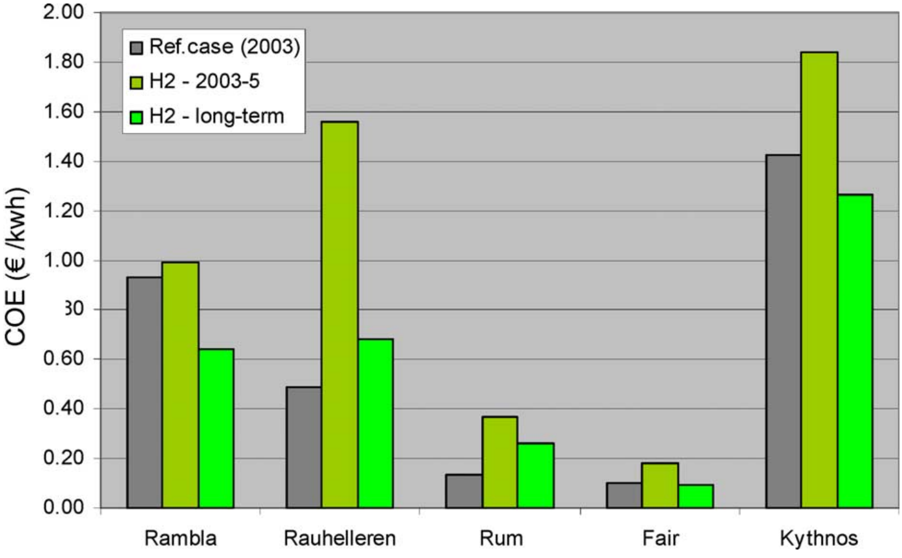

Fig. 4. Comparison of the cost of energy (COE) for the conventional SAPS and H-SAPS in 2003–2005 and in the long-term for the five simulated cases.

almost exclusively recognise the near-term potential for FC power systems based on distribution of hydrogen from centrally produced hydrogen, as the hydrogen production option from RE is too expensive. The source for distributed hydrogen, with Air Liquide and Linde as main actors for Europe, are almost exclusively fossil (steam reforming of natural gas) [16].

In the present modelling study, the two PV-based H-SAPS systems situated in southern Europe, and the Fair Isle wind/hydrogen system, were found to be able to compete with conventional power SAPS. The PV-based systems are situated in sunny regions and have low energy and power demand at night. This gives a smaller energy storage demand. Energy storage is needed on a weekly, rather than monthly or seasonal basis. The prospects for Fair Isle system also appear favourable in the long-term. This is mainly due to extremely good wind resources and a system, which even today seems to be slightly over-dimensioned. Rauhelleren (wind/hydrogen) and Rum (micro-hydro/hydrogen) both have limited RES compared to the load and the energy storage need becomes seasonal.

3.2. Market assessment

The assessment of the market for H-SAPS was divided into demand side, supply side and external factors affecting both the demand and supply.

3.2.1. Demand side

An essential part of a market analysis is the demand side; the users. The market demand for an innovation (hydrogen technology in SAPS) will depend on three major aspects at

the very least:

- The external conditions of the market
- The characteristics of the demand side use of the target market
- The degree of diffusion and acceptance of the technology

The users were grouped in three different segments, depending on their current situation with respect to availability of electricity (external conditions of the market):

- Segment A: high cost grid connected users
- Segment B: conventional SAPS users
- Segment C: non-electrified users

Several difficulties were encountered when trying to quantify Segment A. This was mainly because the information on high cost grid-connected users was only available on a local level from the local utility companies. In addition, most of the utility companies were not aware of stand-alone power supply as an alternative to grid extension. The general policy was to set a standard charge for electricity across the board for customers in both rural and urban areas. As a result, stand-alone power supply was rarely included in energy policies. In this segment, the major market barrier is the current cost of service for the alternative, grid-connected systems. Few companies have looked at the costs per type of user, due to the lack of awareness. In addition, a general lack of incentives for private wires and for regulations was apparent.

The most promising markets for this segment are the electrified customers that would want to disconnect from the grid for the following reasons:

(1) The grid connection is too expensive to maintain and operate for the grid owner and there is no obligation to upgrade the connection and supply the "expensive" customers
(2) A segmentation of costs from the grid owner results in a high cost for these particular customers rendering SAPS and H-SAPS an attractive alternative
(3) The customer is not satisfied with the quality of the electricity supplied through the grid.

In light of the assessment of Segment A, Segments B and C were identified as the best potential market for RE-SAPS and H-SAPS. There are two main competitors: diesel engine generator sets (DEGS) and grid extension. The principal market barrier in this segment is high upfront costs, which still deter potential users. Moreover, the end-user does not possess knowledge of the available technology. National energy policies do not offer appropriate regulations for this sector. Demand side management and rational use of energy (RUE) may, however, make RE-SAPS and H-SAPS more economically attractive than diesel SAPS or grid extensions.

It was found that a more detailed classification of the users was required in order to assess the demand side market potential for H-SAPS. The demand side was therefore characterised according to the type of consumer. The groups found to represent the market were:

1. Residential electricity supply
2. Agricultural activities

3. Tourism
4. Water treatment and desalination
5. Back-up power systems
6. Communication
7. Others (lighthouses, food processing, etc.)

Table 9 shows the estimated potential for future H-SAPS installations in Europe. The numbers are based on a study [17], questionnaires to energy institutes and authorities in all European countries, questionnaire and telephone contact to authorities in the partner countries (Spain, Norway, UK, Ireland and Greece) and internal reports from the study partners. It is important to notice that the estimate of the market size estimate was based on "counting" and did not include any assessment of external factors. It is therefore likely that the different market categories will be developed at varying stages. Although the existing 170,000 non grid-connected houses in Romania will not become a market for H-SAPS in short-term due to the unfavourable energy policy climate in Romania which is a typical Candidate Country from Eastern Europe with a weak electricity grid.

The social attitude of potential H-SAPS users with respect to the introduction of the H-SAPS technology was also investigated through questionnaires at one of the chosen case study sites. The on-site investigation at La Rambla del Agua, a current RE-SAPS, identified a severe lack of awareness of the potential of even SAPS as a definitive solution compared to grid connection. The majority of users considered SAPS as an interim solution until grid connection could be obtained. This might not be the case for all communities, but gives an indication of the amount of work that needs to be undertaken in order to promote SAPS and H-SAPS as stable and permanent energy demand solutions. The survey identified a distinct

Table 9
Summary of the estimated future potential market for H-SAPS in Europe

	Number of dwellings (users) covered	Unit power (kW)	Total power (MW)	Total annual energy demand (GWh)
Rural villages, settlements and rural housing	500,000	3	1500	1601
Back-up power systems	2000	5	10	7
Rural tourism establishments	10,000	5	50	37
Rural tourism establishments with strong energy requirements	1500	30	45	30
Rural farming and ranching	200	40	8	4
Water desalination plants (small)	550	4	2	4
Waste water treatment	450	10	5	10
Large communication stations	150	10	2	13
Total			1621	1706

lack of knowledge of future solutions, such as H-SAPS, which is considered as an important market barrier.

From the experience of the partners, it was concluded that the main objective for the introduction of H-SAPS would be the achievement of three levels of integration:

- Social use
- Managerial–technical
- Physical

The installation of a H-SAPS would have a major impact on the end-user, hence social attitudes and issues constitute the most important area. However, the managerial and technical aspects must also be taken into consideration, to convince them that H-SAPS and RE-SAPS offer more than just an interim solution before the arrival of the grid. They should be seen as the definitive solution. Physical integration should also be considered. Minimising the visual and physical impact of the new technology in the environment is vital to overcome social barriers.

3.2.2. Supply side

The supply side of the market was divided into two main groups:

(1) operational market players
(2) visionary market drivers

The two groups and their different roles are briefly explained as follows:

The development of a hydrogen related market for which the technology is not expected to become mature and cost-efficient in the next 5–10 years cannot rely on cost-benefit incentives or profit driven business decisions from the average commercial player. This will particularly be the case for smaller technology developers that cover the various bits and pieces of more complex energy systems involving hydrogen. Without clear short-term commercial incentives, these market players will not produce quick returns.

In the context of the present study, as many as 131 companies and institutions (technology developers and system providers) joined the network as interested parties on the H-SAPS supply side. The information was gathered at the workshops and through interviews/questionnaires. Table 10 provides some aggregated figures on the type of market players who consider they are H-SAPS stakeholders or interested parties.

The long-term hydrogen related market developments must rely on the major, long-term and visionary market drivers. These are the large energy companies with objectives reaching well into the next 2–3 decades, both with regard to commercial achievements as well as their responsibilities to society. Companies, such as Shell, BP, Norsk Hydro can have a real impact in the market place and when these significant actors go public with their visions for the development of a hydrogen economy, the market will listen. There will always be more detailed strategies and work programmes to substantiate these visions. These work programmes will be based on scenarios and shorter-term actions/funding for technology and market developments, giving the technology suppliers sufficient incentive and prospects for short-term cost/benefit and profit.

Table 10
H-SAPS interested parties

EU	1	
Energy system	9	
Utility and power	2	
Owners and operators	3	
Renewable energy technology	47	
Fuel cells and hydrogen technology	30	
Electrolysers		12
Fuel cells		8
Hydrogen storage		10
Compressors		7
Energy engineering, research institutes and consultant companies	20	
Hydrogen/renewable energy associations, networks and magazines/publications	19	
Associations and networks		12
Magazines and publications		7
Total	131	

As Fig. 5 indicates, there is a number of possible developments towards a viable hydrogen market, and there is little doubt that the main future potential market will be the mobile market. It is, however, not so clear when and how fast this market will develop.

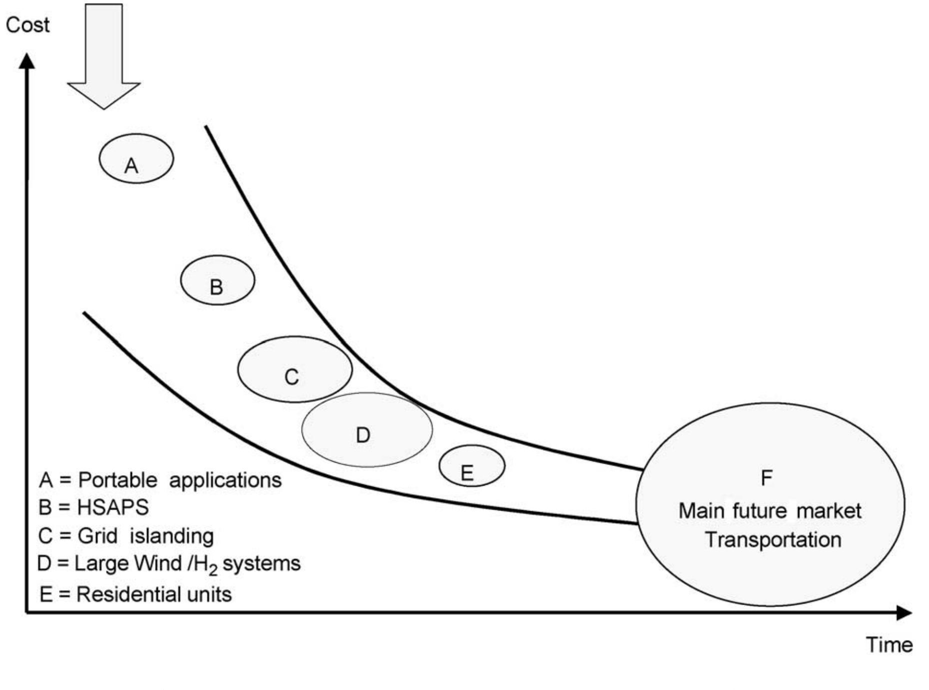

Fig. 5. Schematic presentation of the route to market for hydrogen applications.

Fortunately, there will be some niche markets along the way, which will give sufficient possibilities for profit, hence giving the technology and infrastructure developers the necessary incentives to put their best efforts into their specific role in the market development.

H-SAPS will probably be one such niche market, and the target groups will by and large be high cost applications to serve the market niches described in chapter 3.2.1.

Islanded operation of distribution networks will be another, aiming at alternatives to traditional grid investments. However, there are a number of issues to be resolved in this specific context, but there is little doubt that H-SAPS and Grid Islanding will work along the same path, either as competing solutions, or as complementary solutions in an integrated system.

The long-term perspective implies that national governments and international public institutions must play a key role. However, the policies and limited public funds must support the strategies of the visionary market drivers. The authorities must see these visionary market drivers as their closest allies and adopt their visions and strategies as the basis for their policy making.

3.2.3. External factors

Work was undertaken to carry out a validation of the statistical material used for assessing the market potential in the various markets addressed. This activity included a description of the current status for such market validations, the aims of the validation and the results obtained for the H-SAPS partner countries, Greece, UK and Norway, as well as Ireland.

Many of the input parameters used for traditional market assessments (costs, life-time, price sensitivity, public awareness, etc.) are far from being available for H-SAPS as of today, so there is in fact no straightforward methodology in existence. Therefore, a specific model for this assessment was developed.

The H-SAPS Model aims to provide a qualified assessment of the potential H-SAPS market in certain regions in Europe. This will be undertaken by developing a set of qualitative indicators of certain external factors other than the more technology related factors that are seen to affect the size of a RES market in which the H-SAPS market will have to develop. These will be sufficiently good indicators that can give a picture of the maturity of the framework conditions in which the H-SAPS market will have to develop [16].

The external factors are:

- Energy policy factors:
  - General political climate—for RES
  - Energy mix—for RES (security of supply, diversification, environment)
  - Subsidies and Fiscal measures—for RES (tax incentives, certificate trading, etc.)
  - Implementation of the RES electricity directive
- Other factors:
  - Security and quality of supply (blackouts, natural disasters, terrorist attacks)
  - Population and public perception
  - Formal procedures in local planning (environmental regulations, local planning)
  - Grid system and cost issues

3.3. Environment and RE utilisation

In order to evaluate the potential for hydrogen technology as an RE enabler in SAPS, computer models for short-time frequency and voltage stability evaluations were set up. Furthermore, the potential impact on the environment and the utilisation of renewable energy in Europe upon realisation of the H-SAPS market was estimated using the market quantification from the *Market Potential Report*.

3.3.1. Environmental impacts

The size limitations (up to 300 kW_{el} generation) and energy system type (SAPS) chosen strongly influence the impact, which can be made on the environment on a European level. It was assumed that 50% of the largest market segment, the "rural villages, settlements and houses" from Table 9, had diesel based power generation and that the total (maximum) energy demand supplied by diesel was around 1 TWh (~900 GWh). This is less than 0.0001% of the total annual electricity generation from stationary applications in Europe.

The total CO_2 emissions saved by the introduction of H-SAPS into these marked segments were then estimated to be annually around 1 million ts CO_2. The potential emissions savings for CO_2, CO, NO_x and particles are summarised in Table 11.

On a local scale, the environmental impact of integrating 100% renewables is of course greater. In pristine areas with a topography that does not allow for a high rate of air circulation, NO_x and particle emissions to the air may be of great negative impact to the environment. For rural tourism, and especially so-called eco-tourism, NO_x, CO and particles may be of a special concern. These local emissions may be avoided all together by using distributed hydrogen or hydrogen generated from RES. Noise pollution, which is often overlooked, is another important issue for rural applications that are important for user categories like tourism and rural residences, but perhaps less important for communications, water treatment and other technical/commercial installations.

3.3.2. RE utilization

3.3.2.1. Technical potential. As an example the European standard BS EN 50160 [18] sets requirements on non-interconnected (i.e. stand-alone) system to achieve the following:

- 50 Hz ±2% (i.e. 49–51 Hz) for 95% of week; ±15% (i.e. 42.5–57.5 Hz) for 100% of week

Table 11
Estimates for annual emissions savings on a European scale

Emissions	With gas cleaning technology	Without gas cleaning technology
CO_2 (t/yr)	~1,000,000	~1,000,000
CO (t/yr)	~2100	14,000–28,000
NO_x (t/yr)	~2300	4600–14,000
Particles (t/yr)	~130	300–1400

- 230 V $\pm 10\%$ (i.e. 207–253 V) for 95% of week
- over 1 week, 95% of the 10 min rms values of negative phase sequence component shall be within 0–2%, of positive phase sequence component

On the basis of stability issues, the potential for hydrogen as an RE enabler was investigated through short time modelling of mini-grid stability. An existing 20 kW wind/diesel system was modelled with and without a hydrogen energy system. The wind/hydrogen SAPS is shown in Fig. 6. In this set-up the FC is connected to a DC-motor and synchronous compensator in order to provide reactive power to the AC mini-grid.

These preliminary test runs encouraged the use of electrolyser both as a resistive load controller and a hydrogen production unit in order to store renewable energy as hydrogen for re-electrification during deficit wind power. Through the implementation of an electrolyser into the wind-H-SAPS, the system power quality, mainly the frequency and voltage, was not found to differ significantly from the wind-SAPS without the electrolyser. In fact the system frequency was observed to be more stable when the electrolyser operated in parallel with the load controllers, especially during high excess energy in the system.

It was also pointed out that the electrolyser needed more ON&OFF switching parameters in addition to the system frequency. Average wind speeds, for example, for the last 30 min and the derivative of system frequency were suggested as additional parameters for the

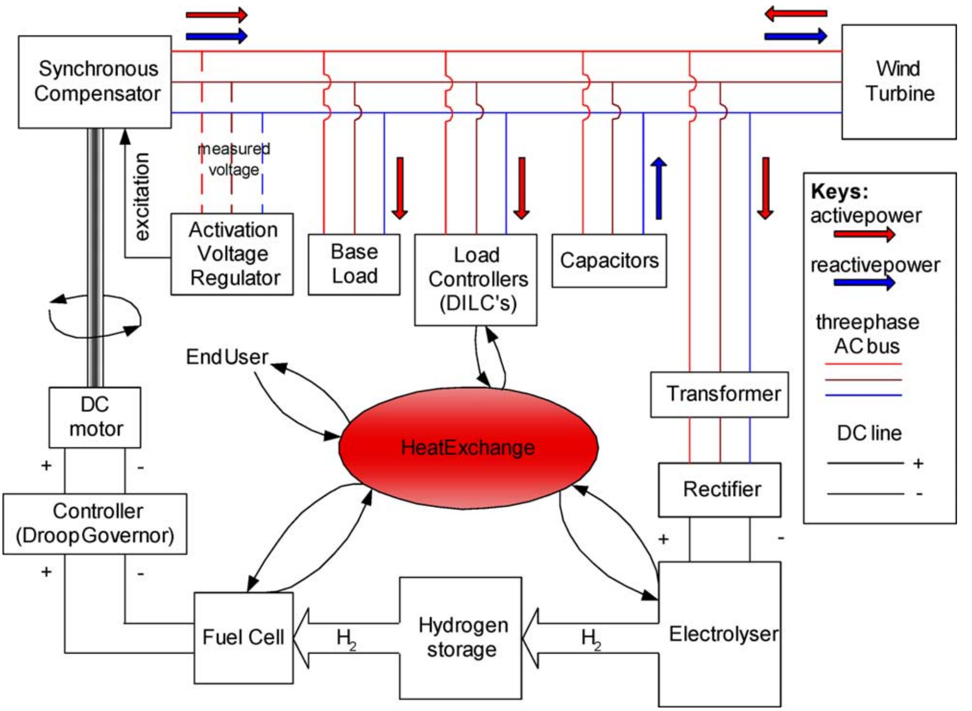

Fig. 6. Schematic of the layout of the wind-H-SAPS.

electrolyser ON&OFF switching, thereby reducing the risk for electrolyser start-up at lower wind speeds [19,20].

It was found that the electrolyser operation needed careful control in order to avoid unnecessary FC start-up when frequency falls as a result of windmill and electrolyser power mismatch [21].

3.3.2.2. RE utilisation potential. Installed RE capacity in a RE-SAPS is often 2–3 times higher than the electricity output from the energy system. In this work a factor of three was used. This depends strongly on the RES on the site, but a general estimate was assumed that one should not go below the ratio of 3. A higher ratio was interpreted as a site where one would not consider building a RE-based (PV, wind, micro-hydro) SAPS or H-SAPS. Based on the installed capacity of around 900 MW_{el} on the generation side (Chapter 3.3.1), a maximum potential of about 2.5 GWel installed RE capacity was estimated. The total electricity generation from renewables in the OECD countries in 1998 was 630 GWh_{el}.

3.3.3. Impact from other and related markets

3.3.3.1. H-SAPS markets outside Europe. At the beginning of the 21st century, more than 2 billion people, one third of the world's population, did not have access to a reliable electricity supply.

In Africa it has been estimated that only 10% of urban households have an electricity supply and the fraction of rural households supplied is much less. Table 12 shows the percentage of the rural population with access to electricity in various regions of the world.

Assuming that a significant proportion of these communities would be best served by stand-alone generation, then the potential market for SAPS and ultimately H-SAPS, is extremely large. This market would be primarily found in the world's developing countries, but in this case, the availability of funding sources is one of the most important success factors.

3.3.3.2. Grid islanding. Island operation of distribution networks is strongly related to stand-alone operation and may provide favourable conditions for the deployment of RES. Furthermore, the combination of RE technologies in distributed generation and island operation of the grid would benefit from temporary energy storage for technical grid balancing or other strategic purposes.

Current design of networks discourages the 'island' operation of small parts of the network when the in-feed is lost for safety and security reasons. As the amount of generation, which is embedded in the distribution networks increases, this policy will need

Table 12
Rural population access to electricity

Region	% Rural population with access to electricity
Latin America	27
Asia	19
North Africa	21
Rest of Africa	4

to be reviewed. There is, at present, no studies on the potential for such H-SAPS related distributed RE-energy systems in Europe.

4. Recommendations

The results drawn from the current study and the respective recommendations are addressed to governments, the research community and industry. The recommendations include targeted market research, establishment of individual cost targets, regulatory changes to facilitate alternative grid solutions, information and capacity building, focused technology research, bridging the technology gaps and development of a CEN standard for SAPS.

4.1. Targeted market analysis

It is foreseen that in the future market, H_2 use in the transportation sector is by far the largest market sector but also technologically the most demanding (Chapter 3.2.2). When the technology is available and the costs well defined, implementing an infrastructure to serve such a large consumer application will provide a basis for a larger and more diverse market, the classic example being the development of the natural gas market. However the technology for using H_2 in transport applications (vis. vehicles) is under development, especially in the US. In addition H_2-fuelled ICEs are a near-term possibility. Therefore a dual approach is recommended, where both the infrastructure development (top-down) and the technology development (bottom-up) are facilitated.

The market opportunities were briefly outlined and shown in Fig. 5. The more knowledge can be gained with regards to these smaller emerging market possibilities, the better forecasts can be made with respect to cost targets and need for infrastructure development. Furthermore, as these smaller markets will be changing rapidly the market developments should be monitored and updated at regular intervals during the technology development.

Targeted market analysis following the step-by-step technology-cost development will facilitate reasonable and well-defined targets. The consequence of setting unrealistic and too long-term targets is often disillusionment and abandonment of the technology. In particular, the policy makers have a long track record in leaving policy targets behind if the technology and cost targets are not met on schedule. Targeted market analysis for the following most apparent small scale/high cost market applications along the way towards the large volume transport market are thus recommended:

- Portable applications
- H-SAPS
- Grid islanding
- Large wind/H_2 systems
- Residential units

4.2. Individual cost targets

As a direct consequence of the recommendation above, the technology developers should be involved in the target setting of the components and systems required for the applications

listed. Specifications on the technology needs will emerge from the market analysis mentioned above. However, each component and system configuration should be made subject to specific cost targets. There are already examples on this type of cost target contracting, and the feed-back from the technology developers is very positive e.g. IRD's (Innovation Research Development—Denmark) Cost Target Contract with the European Commission to achieve 3000 €/kW for a FC.

4.3. Regulations facilitating alternative grid solutions

Current regulation discourages the operation of 'islands' within the grid when the in-feed is prohibited for safety and security reasons. As the amount of generation, which is embedded in the distribution network increases this policy needs to be reviewed. Such a review is currently ongoing in the UK, and the same should be done elsewhere in due time. This may represent a window of opportunity for H_2 applications in a not so distant future. Regulations facilitating "Grid Islanding" and particularly in-feed of surplus electricity generation are thus recommended.

4.4. Information and capacity building

SAPS are not even on the utilities' list of possible solutions offered to even high cost consumers in Europe. Consumers do not request this since they are not made aware of the option. Thus the regulatory bodies, the grid operators and the professional consumers should be involved in a large scale effort to present SAPS, H-SAPS and alternative grid solutions as viable options in niche situations. Policy measures, targeted information and capacity building efforts are thus recommended towards these actors.

In the context of sustainable communities, the information with regard to technological and economical potential of H_2 applications, SAPS and H-SAPS must be made available to the key actors, both at the level of European and national policy-makers, at the industry level and not least at the level of local energy planners. The appropriate instrument to be used to reach the identified actors should be further evaluated.

4.5. Development of a CEN-standard for SAPS

At present there are no common technical standards for SAPS in Europe. Particularly in view of the upcoming efforts to support the emergence of Sustainable Communities, the issue of establishing EU-wide standards/mechanisms on local energy planning will become key. The standards should cover issues including safety, power quality and frequency stability. The European Commission should assess the potential impact of supporting development of European and International standards, such as IEC standards for local energy planning.

In addition, the use of hydrogen technology should be included in existing relevant standards. Safety in handling of hydrogen gas is of particular importance. A CEN (European Committee for Standardisation) standard specifically for handling of hydrogen gas is thus recommended.

4.6. Demonstration projects

Demonstration projects are a vital tool in the process of proving the ability of technology to solve a specific task. The potential users of H-SAPS reflect user categories for other potential hydrogen markets such as RE-hydrogen solutions for grid islanding and RE-hydrogen solutions for grid-connected distributed generation systems (e.g. in weak grids). In this way H-SAPS demonstration plants may pave the way for other RE-based systems with hydrogen as an energy carrier. Demonstration will also facilitate the development of standards. Furthermore demonstration of H-SAPS and in turn grid-connected RE-hydrogen systems for distributed generation might prove valuable in order to establish the feasibility of higher RE penetration through hydrogen technology.

In terms of future demonstration plants, the system modelling showed that the cost of the H-SAPS is high and that the main problem is to limit the storage demand. A direct consequence of this would be to make sure that any demonstration or test plant is situated ideally with regards to RES and match of RES and user load.

Another important issue is the division of electrical and thermal load in order to raise the total energy efficiency of the hydrogen energy system. In addition, it is important to recognise the need for prioritising of loads by introducing load control, as is done in a number of conventional SAPS systems. This is a powerful tool in reducing COE for the system.

Control systems with incentives for the use of energy in times of surplus RE are another means to reduce the investment costs for production and storage of energy as hydrogen in H-SAPS.

4.7. Applied RTD

There are, and there will likely be in the future, aggressive targets on European level for the percentage of RE penetration in the energy mix. Storage of energy as hydrogen might in the long-term be critical for the inclusion of large amounts of intermittent RE in the European energy mix both for stationary or transport applications. Giving focus on hydrogen as an RE enabler is extremely important.

In the H-SAPS study, the following critical technical barriers were identified (in prioritised order):

- High costs of both electrolyser and FC components
- Low energy ‘round-trip’ efficiency of the hydrogen energy system—especially critical for small systems
- Development of easy-to-use and energy efficient gas and electricity control systems
- Short lifetime warranties and little lifetime experience for PEM electrolysers and PEM FCs

4.8. Bridging technology—short and medium term

Severe hurdles with respect to costs for hydrogen production and hydrogen re-electrification through electrolysis and FCs, respectively, have already been described in the previous paragraph. In addition, hydrogen storage options prove expensive especially in

areas where the RES and load match is not adequate and the energy storage needs are approaching seasonal fluctuations. It is therefore important to look at intermediate steps such as hydrogen ICE for re-electrification of hydrogen.

Another important issue is to look for market possibilities where hydrogen could offer a compact and cost effective solution even with centrally distributed hydrogen. Even though the R&D focus for AFCs is much lower than is the case for PEMFCs, mainly because of the focus on PEMFCs for mobile applications, it is important to keep this solution in mind. AFCs may prove, at least in the short-term, to be the preferred solution for H-SAPS and stationary applications in general. SOFCs could also be studied as a follow-up of the current paper.

Acknowledgements

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Appendix A. Plan for demonstration Projects

Demonstration projects are recommended as a tool in market development, particularly to prove the ability of the technology to perform a specific task in a real environment and may also facilitate development of standards. Furthermore recommendations with regard to the characteristics of future demonstration plants are provided (chapter 4.1.6). The critical success factors for market development identified through the SWOT analysis are not applicable to the individual project level. The recommended characteristics for future demonstration plants are applied as key factors for success in the selection of the demonstration projects.

Two demonstration projects are recommended as H-SAPS demonstration projects. Both projects are selected from the five case studies carried out during this assessment.

The two cases selected are Rambla del Agua and Fair Isle. The key driver of this choice is that the hydrogen solution appears to become economically viable in the long term. Both projects are situated ideally with respect to match between user load profile and RES energy production. Furthermore both projects also accompany intelligent load control and load prioritising (Fig. A1).

One of the cases uses PV generation and the other wind and thus the demonstration projects will provide distinct findings relevant to each generation technology. Furthermore one is southern Europe and the other northern Europe. This means the projects will highlight the differences in demand profiles and climatic conditions and allow for an assessment on the implications of this for the hydrogen technology and its effectiveness.

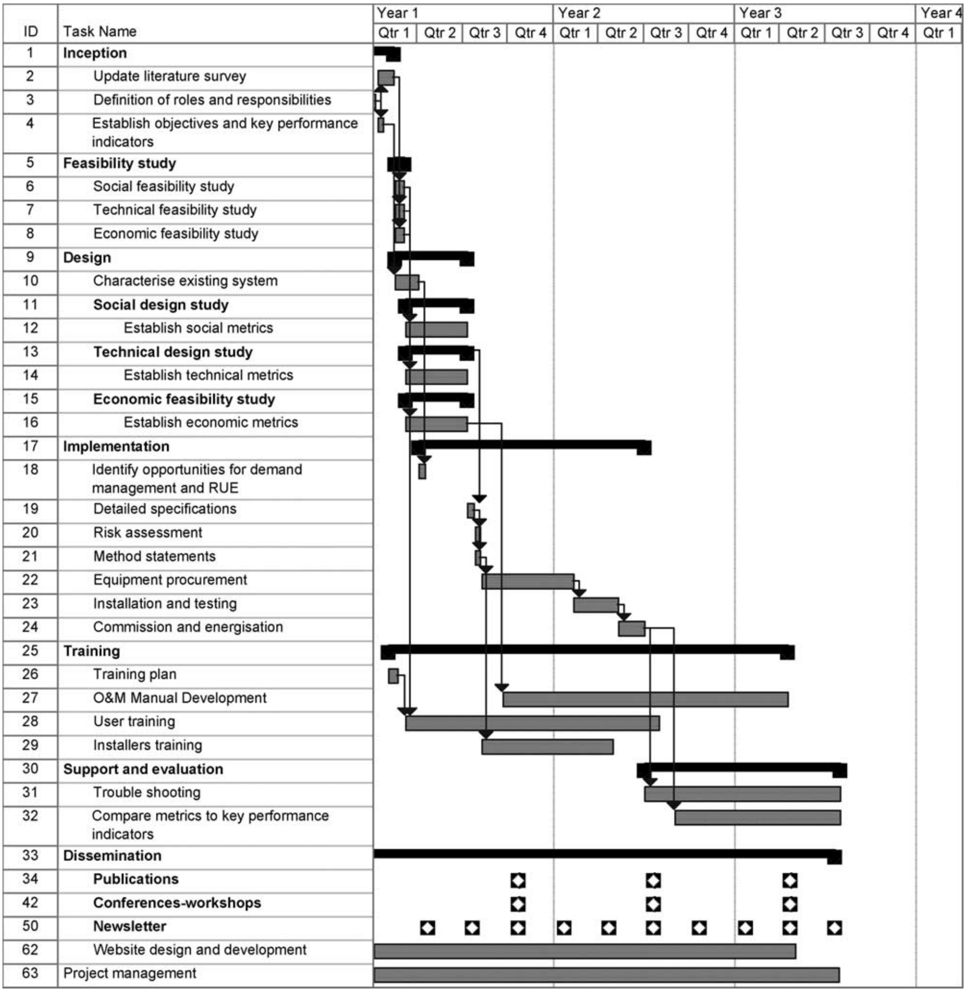

Fig. A1. Work Programme for Rambla del Agua and Fair Isle.

A.1. La Rambla del Agua

La Rambla del Agua is a small village situated at an elevation of 1600 m in the Natural Park of Sierra de Baza, 80 kms east of Granada (Andalusia). A 10,230 W_p PV-hybrid system was installed in 1997 by TTA through a project funded in part by the inhabitants (37%), the program PAEE of the Spanish Industry and Energy Ministry (40%) and by the European Commission in the scope of the project THERMIE SE/218/95NL-DE-ES (23%).

A large proportion of the generated energy from the PV-panels is dumped over the year. Through the energy flow modelling the potential for the introduction of a hydrogen energy

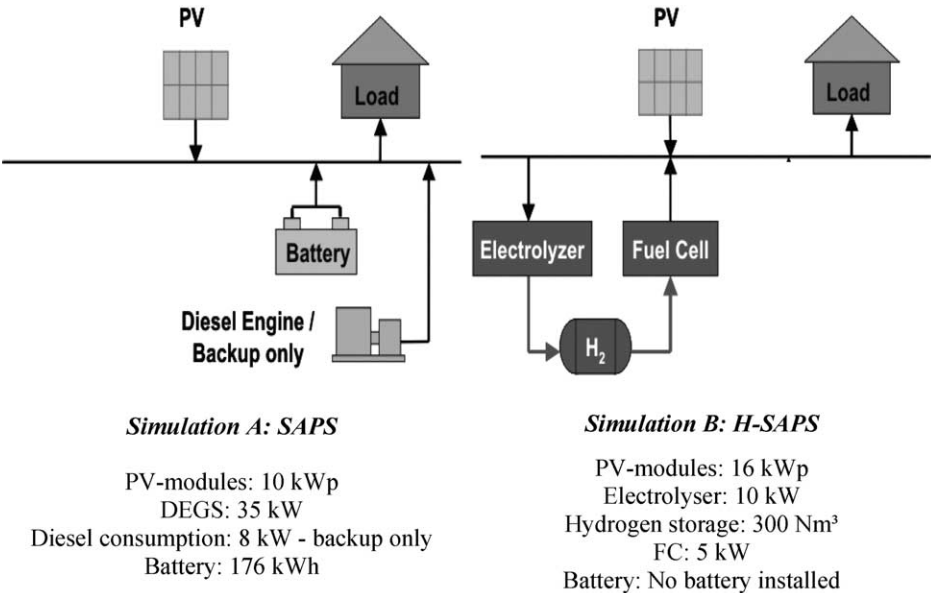

Fig. A2. Design parameters of the conventional SAPS (PV/battery) and the H-SAPS (PV/hydrogen) system at Rambla del Agua.

system to replace the large batteries was examined. The design of the conventional SAPS and the virtual H-SAPS is given in Fig. A2.

An attractive demonstration plan will have to be put in place to persuade the users to accept the new technological solution. Previous studies of the social acceptance of the already existing RE-SAPS system will provide comparative data (comparing metrics to key performance indicators).

A.2. Fair Isle

Fair isle is a small island lying halfway between Orkney and Shetland with a population of about 70 people. Electricity and heat is generated from a wind/diesel mini-grid energy system consisting of a 35 kW Diesel Engine Generator Set (DEGS) and two wind turbines of 60 and 100 kW, respectively. A very attractive pricing structure has encouraged the inhabitants to use 'dump'-electricity from the wind turbines for heating.

The potential for introduction of hydrogen is high. Over-capacity, in terms of energy, is installed and instead of dumping wind energy, this energy could be used to produce hydrogen. Over the year 60% of the wind energy is being dumped (a small part of the dumped energy is, as explained above, used for domestic heating).

The system design for the conventional SAPS and the H-SAPS is shown in Fig. A3. The diesel engine generator set is replaced entirely with a hydrogen energy system. The overall energy efficiency (calculated over the whole year) is found to be ∼30%. It was found that over-dimensioning of the windmills was not necessary when introducing a hydrogen energy system due to the extensive dumping of energy in the system.

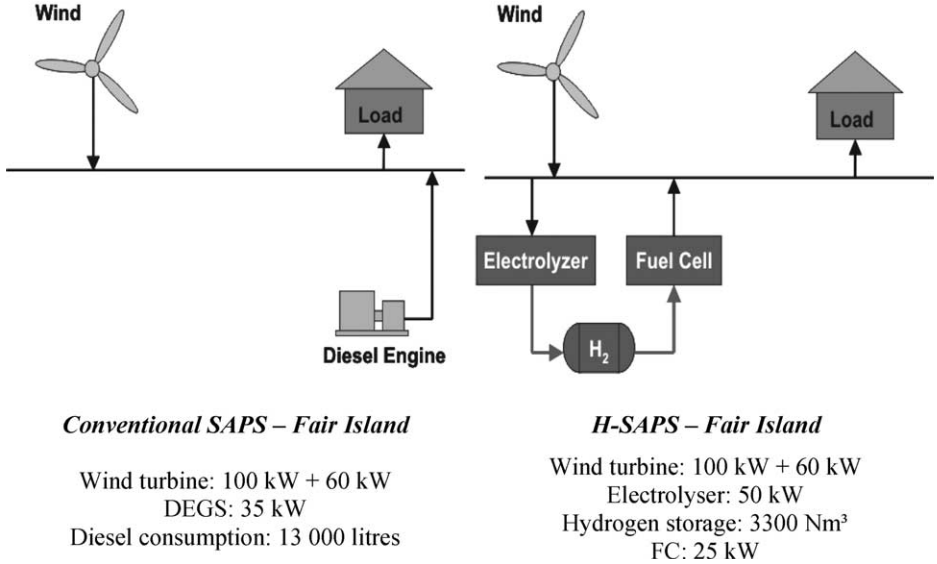

Fig. A3. Design parameters of the conventional SAPS (wind/diesel) and the virtual H-SAPS (wind/hydrogen) system at Fair Isle.

Appendix B. Acronyms and definitions

RE	Renewable energy
RES	Renewable energy sources
RUE	Rational use of energy
SAPS	Stand-alone power system
RE-SAPS	SAPS with a major part of renewable energy input
H-SAPS	Hydrogen Stand-Alone Power Systems (SAPS with hydrogen as the longer term energy storage option)
ICE	Internal combustion engine
PEM	Proton exchange membrane
FC	Fuel cell
AFC	Alkaline fuel cell
PEMFC	Proton exchange membrane fuel cell
MCFC	Molten carbonate fuel cell
PAFC	Phosphoric acid fuel cell
SOFC	Solid oxide fuel cell
GT	Gas turbine
COE	Cost of energy
R&D	Research and development
GOS	Government organisations
O&M	Operation and maintenance
OECD	Organisation for Economic Cooperation and Development

MW	Megawatts
GW	Gigawatts
PV	Photovoltaic
CEN	European Committee for Standardisation

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